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A stabilized X-band oscillator with frequency control

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A STABILIZED X-BAND OSCILLATOR WITH FREQUENCY CONTROL

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Subj: Thesis entitled "A Stabilized X-Band Oscillator with Frequency Control", prepared by LCDR Clifford W. Bundy as a partial fulfillment for the requirements of a Master's degree.

OR

1. The thesis supervisor, Professor H. J. Zimmermann, assigned the subject thesis a grade of "P", with the following comment:

> "Performance on this project was weak considering the total amount of time involved (in addition to the thesis time, preparatory work was done in a "Special Problems Course"). There seemed to be a lack of the enthusiasm and ingenuity required to keep a research project moving along in the face of the difficulties which inevitably arise."

A STABILIZED X-BAND OSCILLATOR
WITH FREQUENCY CONTROL

by

CLIFFORD WILLIAM BUNDY

B.S., U.S. Naval Academy

1940

SUBMITTED IN PARTIAL FULFILLMENT
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I wish to acknowledge the assistance
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grateful.

ABSTRACT

This laboratory work was conducted to design a system for stabilizing and controlling the frequency of a 2K25 klystron. A functional schematic diagram of the system is presented in Figure 1. If the electrical lengths shown by the dotted and full lines of Figure 1 are made equal, the system will be broad-band in frequency. This broad-band feature was considered to be the primary feature recommending the system.

Stabilization and control of the oscillator over a 30 mcps range with fixed mechanical tuning was achieved. However, the broad-band nature of the stabilization system was not realized in operation.

The amplifier output modulates the oscillator signal at Crystal A in Figure 1.. The upper-sideband is passed through the cavity and mixed with the oscillator signal at Crystal B for detection. The lower-sideband must be suppressed to prevent its travelling through the waveguide path which does not include the cavity, to Crystal B for detection. Two waveguide assemblies were devised to accomplish this suppression. Neither one was too successful in this respect.

Developments of the resultant system of this laboratory work that may be profitable are:

a) Using a reflection type cavity and both side-bands as in the Pound-Zaffarano method of stabilization.

b) Use the conversion of cavity phase-shift to amplifier frequency-shift in measurements.

c) Improve the waveguide assemblies of this thesis to suppress the unwanted sideband.

d) Employ this stabilization method in an F. M. system.

CHAPTER I

INTRODUCTION

A - A Statement of the Problem

This research was undertaken to determine the feasibility of a suggested system for stabilizing and controlling the frequency of a microwave oscillator, namely the 2K25 klystron. The system to be studied may be represented by the block diagram, Figure I.

Assume that the electrical lengths, shown by the full and dotted lines from the oscillator to crystal B, are equal; then the phase fronts arriving at crystal B via the two different paths will be the same. Again, assume that some 30 mcps noise in the amplifier amplitude-modulates the microwave energy incident upon crystal A. If the cavity is tuned to one of the sidebands, the sideband will pass through to crystal B. Here, the carrier and one sideband will recombine to be detected and to provide a 30 mcps input to the amplifier. The zero phase condition for this closed loop requires that if the sideband suffers a phase shift in the cavity, then the amplifier must move away from its center frequency a sufficient amount to compensate the cavity phase shift.

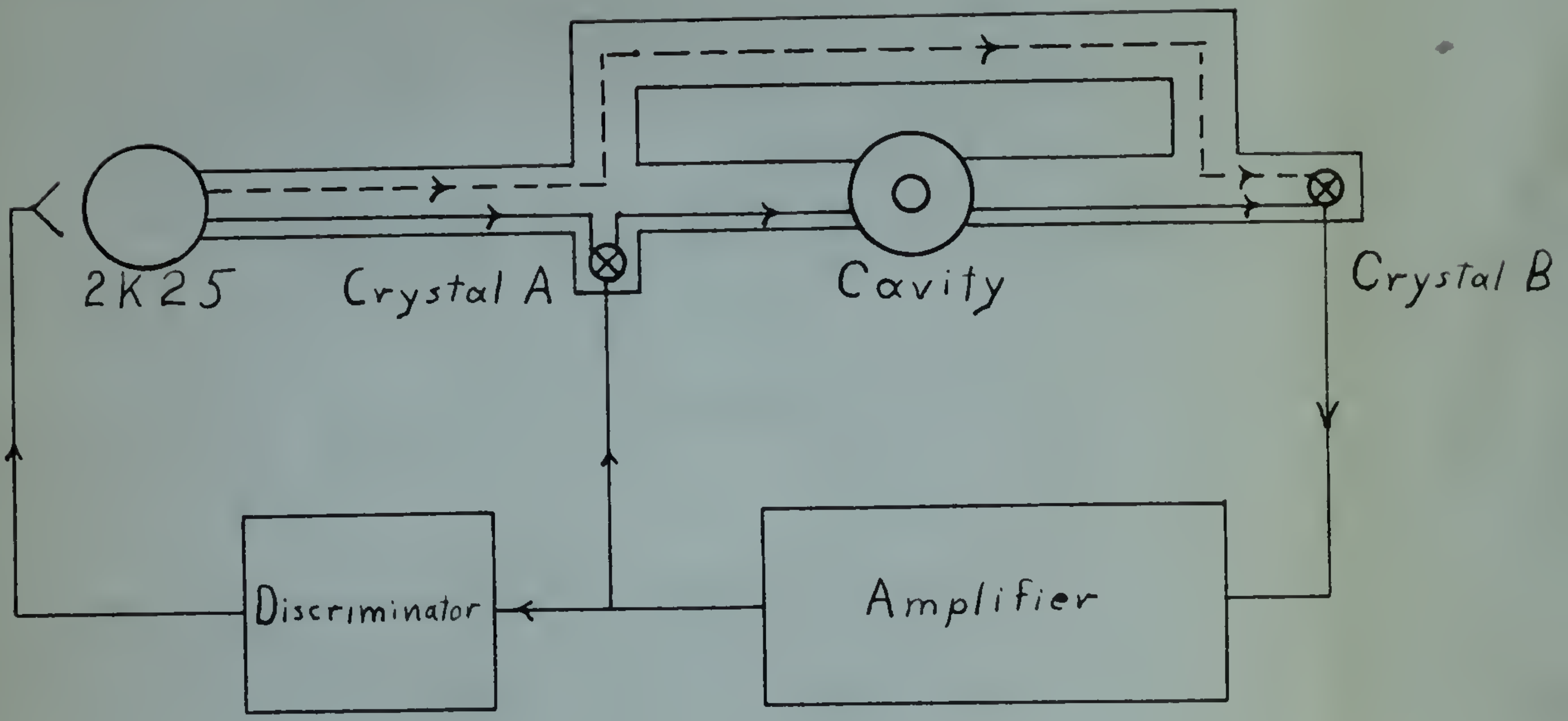


Figure 1

Block Diagram of Proposed System

With the discriminator adjusted to the mid-frequency of the amplifier, a discriminator output will appear whenever the amplifier is forced from its center frequency as described above. Thus, a correction voltage is available and may be applied to the reflector of the 2K25 tube. With the klystron oscillator locked in with the system, tuning the cavity will force the oscillator to track. A frequency-controlled, stabilized oscillator, then, may be realized by this system.

B - Pertinent Previous Work

The problem of stabilizing the microwave oscillator is of importance in the field of communications and in radar applications. R. Dickenson[1] in 1944 developed a stabilization system for a pulsed magnetron. R. V. Pound, working with C.W. Oscillators, subsequently made the most important contributions in this field to date, and his stabilization systems will be briefly discussed.

The first system [2] to be developed by Pound is represented schematically in Figure 2. The output of a microwave discriminator [4] is amplified in the D.C. Amplifier and applied to the reflector of the

reflex klystron to correct the oscillator's frequency to the cavity frequency. This method may be used with the 2K25 or 2K45 klystron and offers single adjustment control over a 10% frequency band with the latter tube. The two disadvantages of the system are:

a) High crystal noise level at audio frequencies which are in the pass band of the D.C. Amplifier.

b) D.C. Amplifier drift.

The microwave discriminator referred to above operates as follows. The energy into the lower Magic Tee, see Figure 2, splits between arms 1 and 3. The energy into arm 1 splits at the upper Magic Tee between arms 1 and 3. Now, the electrical length of arm 1 between the Tee junction and the cavity coupling iris is $\lambda g/8$ greater than the length of arm 3 between the Tee junction and the terminating short. The microwave discriminator functions as a bridge which compares the reflection from the short circuit with that from the resonator. The difference in the outputs, after reflection, of arms 2 and 4 of the upper Magic Tee is of the form of the conventional discriminator curve, Figure 5.

The second method [3] employed by Pound is illustrated by Figure 3 and was developed to avoid

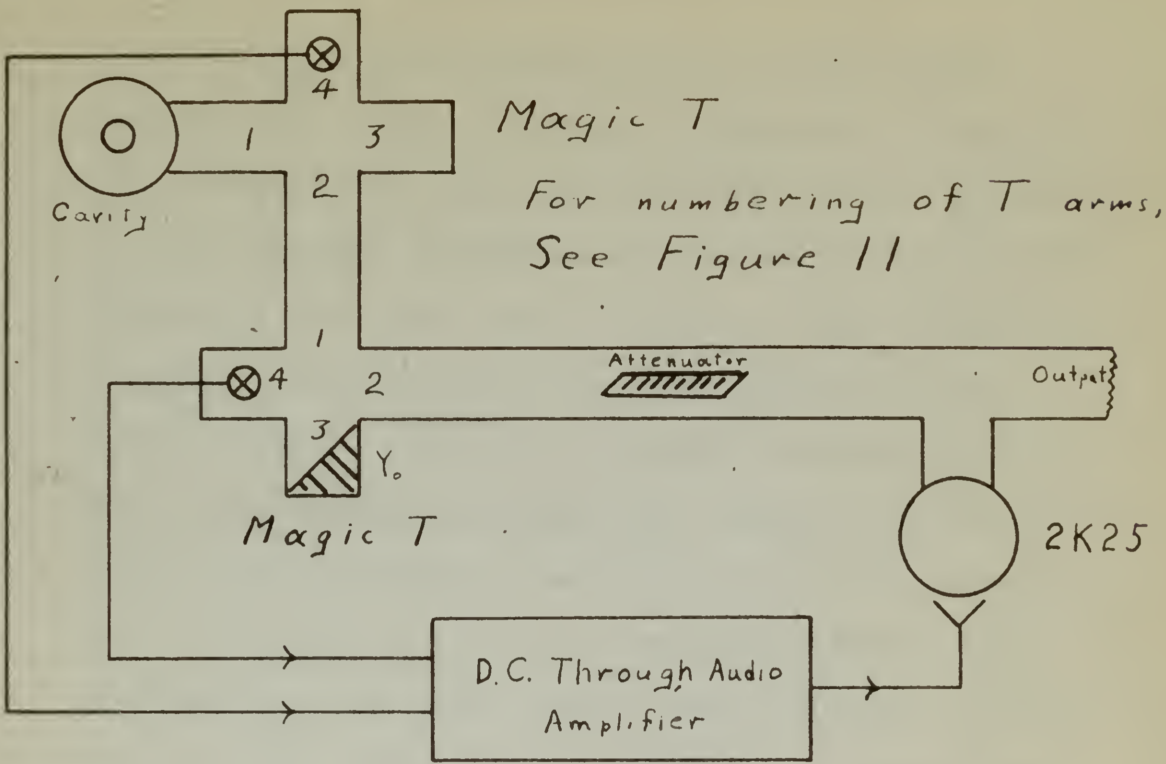


Figure 2 Pound's First System
(Microwave Discriminator)

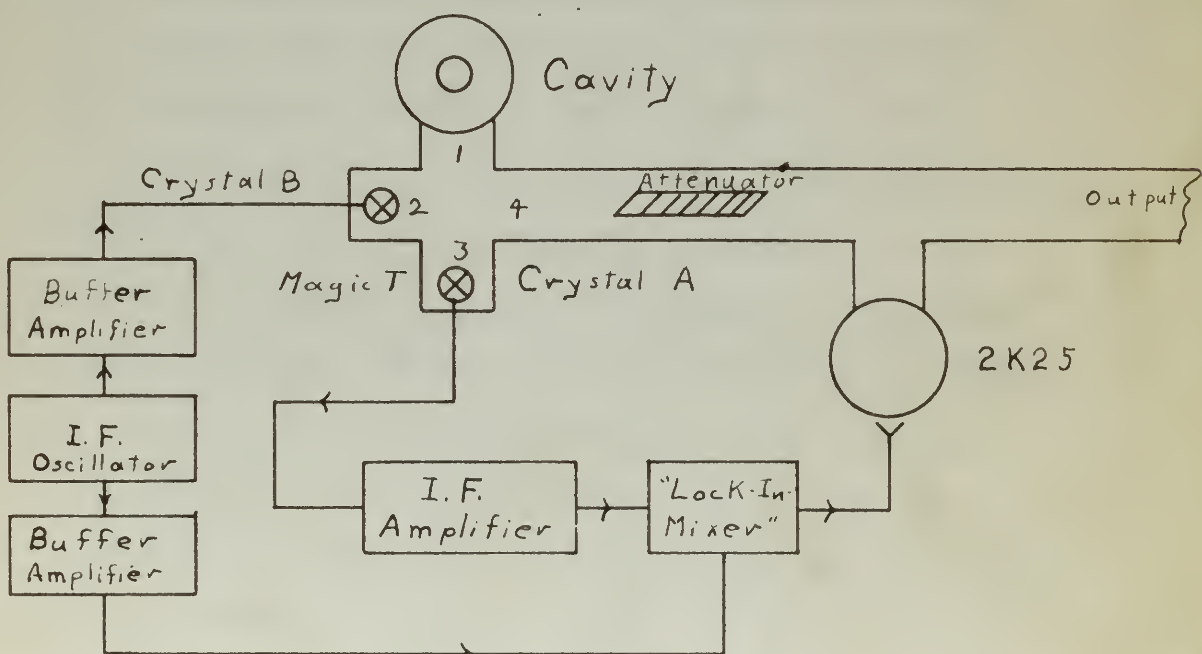


Figure 3 Pound's Second System
Improved By I.F. Components

the two chief disadvantages of the first system. Crystal A presents a matched termination. The cavity reflects incident energy to crystal B. Here, the r.f. energy is modulated at 30 mcps, and the two sidebands developed are reflected. Part of this reflected sideband energy is mixed with the r.f. energy enroute directly to crystal A, which demodulates this amplitude modulated signal. The phase angle of the sidebands relative to the r.f. energy going directly to crystal A is a function of guide lengths from the Magic Tee to the cavity and crystal B and of the reflection coefficient of the cavity. Let the r.f. line length be set to make this phase difference zero for a pure real cavity reflection coefficient which exists when the cavity and oscillator are at the same frequency. Then the phase difference will have a sign corresponding to the sign of the quantity, cavity frequency minus oscillator frequency, when a frequency difference between the cavity and oscillator exists. This sign is preserved in the "lock-in-mixer" whose output corrects the oscillator's frequency to that of the cavity.

F. P. Zaffarano [5] materially improved the performance of Pound's second system by interchanging the functions of crystals A and B. This change interpreted in terms of Figure 3 would mean connecting the I.F. Oscillator to Crystal A of the Figure and connecting the input to the I.F. Amplifier to Crystal B. Then the electrical lengths, attenuator to cavity to Crystal B and attenuator to Crystal A to Crystal B, may be made equal. This change increased the frequency range, increased the sensitivity, and increased the power capacity of the system.

CHAPTER II

EXPERIMENTAL PROCEDURE

First, let us consider analytically the system to be developed, as shown in Figure 1. Figures 4 and 5 represent respectively the phase characteristic of a parallel resonant circuit and the amplitude response of a Foster-Seeley [5,6] discriminator.

E_D = The discriminator output voltage = $K_d\ (f_{amp} - f_o)$

where f_o = the mid-band frequency of the amplifier and discriminator.

f_{amp} = The instantaneous frequency of the i.f. signal through the amplifier.

ΔE_R = Reflector Voltage Change = $E_D + \epsilon$

where the voltage change occurs about the mode-center voltage and ϵ is an error voltage.

Δf_k = Klystron Frequency Change = $-K_o \Delta E_R$

which assumes that Δf_{osc} is a linear function for incremental changes in the reflector voltage.

Phase angle interposed by Cavity = $C\left[f_c - (f_{osc} \pm f_{amp})\right]$

where f_c = cavity midband frequency and f_{amp} is + when the cavity is tuned to the upper sideband.

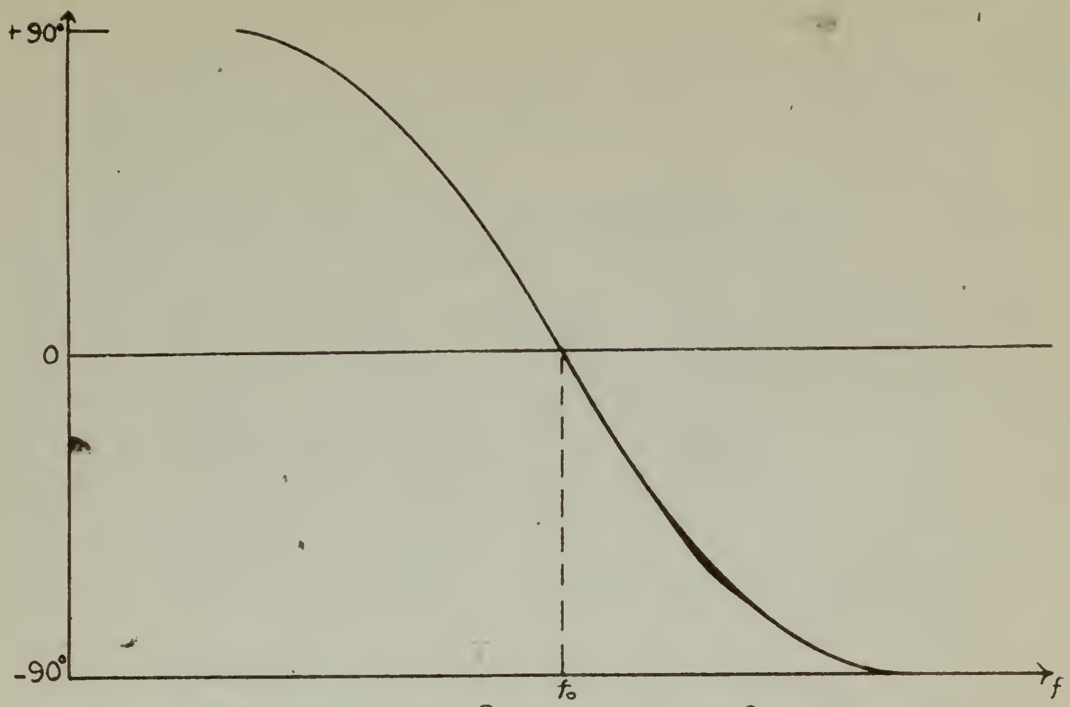


Figure 4 Phase Response of Resonant Circuit

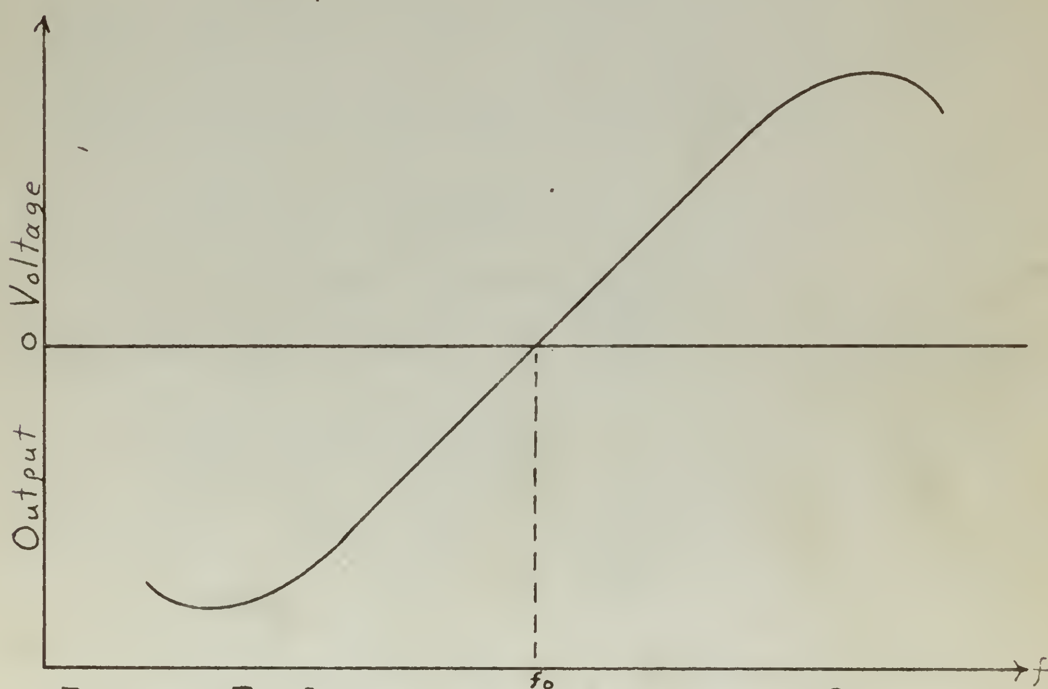


Figure 5 Discriminator Amplitude Response

Phase angle interposed by amplifier = $A\ (f_o - f_{amp})$

The sum of these two phase angles must be equal zero so that they may be equated:

1. $C\left[f_c - (f_{osc} \pm f_{amp})\right] = A(f_o - f_{amp})$

Let f_k = the mode center frequency which has been chosen as the center frequency of operation when

$\Delta E_R = 0$, i.e., f_k is the desired frequency.

Let $f_k = f_c \pm f_o$ [(-) when cavity tuned to upper sideband]

Now $f_{osc} = f_k + \Delta f_k = f_c \pm f_o - K_o \Delta E_R$

2. $$f_{osc} = f_c \pm f_o - K_o\left[K_d(f_{amp} - f_o) + \epsilon\right]$$

Solve equations 1. and 2. for f_{amp}. Then equate these and solve for f_{osc}. The result is:

For upper sideband - - - - - - - - - - - - -

$$f_{osc} = f_k - \frac{K_o\ \epsilon}{1 + \frac{K_o K_d C}{A - C}}$$

For lower sideband - - - - - - - - - - - - -

$$f_{osc} = f_k - \frac{K_o\ \epsilon}{1 + \frac{K_o K_d C}{A + C}}$$

In each case, f_k is the desired frequency.

If $\frac{K_o K_d C}{A - C} \gg 1$, the frequency error using the upper sideband $= -\frac{\epsilon}{K_d C}(A-C)$

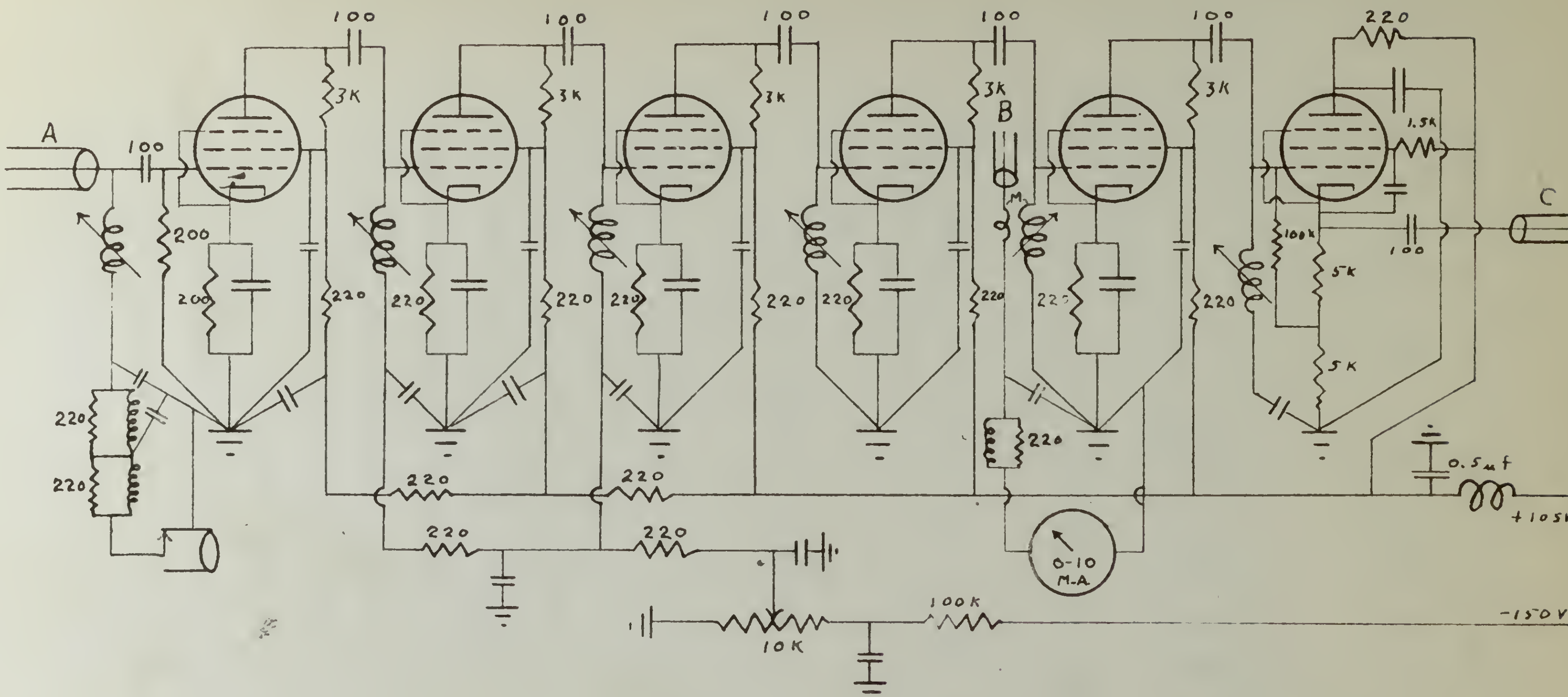
If $\frac{K_o K_d C}{A + C} \gg 1$, the frequency error using the lower sideband $= -\frac{\epsilon}{K_d C}(A+C)$

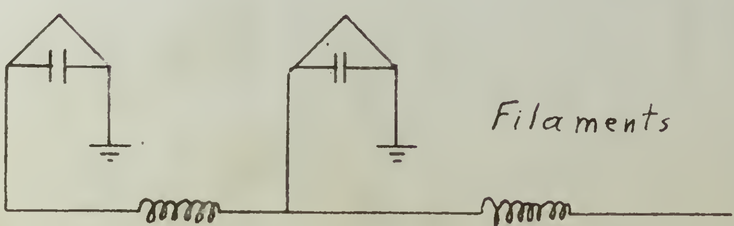
The mathematics indicate that use of the upper sideband would lead to greater frequency stability. No stability observations were made so that this conclusion was not verified in the laboratory work. It may also be concluded that K_d should be as large as practicable. For the upper sideband case, A should equal C; for the lower sideband case, C should be as large as possible and A as small as possible.

It was decided to approximate the condition that A = C in constructing the amplifier. 30 mcps was selected as the center frequency, and the amplifier was built according to the design,[8] Figure 6.

To design the first four stages of the amplifier to make A = C, the following procedure was employed.

A loaded cavity Q of 7000 was assumed at 9000 mcps. If the approximation formula for the phase angle of a resonant circuit is used, the Q_o of each





All tubes -- 6AK5
All resistors ½ watt
All condensers 1,000 μμf unless noted
Tuned inductances --- 18 turns -- #30 wire
Terminal A ---- Input
" B ---- Output to modulator X-tal
" C ---- " " discriminator

Figure 6 30 m.c.p.s. Single Tuned Amplifier

stage of the tuned amplifier may be readily found.

$$2nQ_o \frac{\Delta f_o}{f_o} = 2Q_c \frac{\Delta f_c}{f_c}$$

Set $\Delta f_o = \Delta f_c$ which corresponds to $A = C$

$$Q_o = \frac{Q_c f_o}{nf_c} = \frac{7000}{9000} \times \frac{30}{4}$$

$n = 4$ stages

$Q_o = 5.8$

With the 6AK5 capacities, a load resistor of 2.9K satisfies this condition. The gain per stage will then be 14.

The RCA Sweep Generator was used in lining up the six stage amplifier. The first step in the procedure was to line up each stage individually. This was accomplished by applying the sweep generator input to the grid of one tube; the plate circuit of this same tube was then adjusted to 30 mcps center frequency by observing the output of the following tube (used as a buffer stage) on an oscilloscope.

Subsequently, the overall amplifier response was viewed on the oscilloscope. Then the individual stages were tuned in sequence three to four times until as each stage was tuned either side of the center frequency, the peak of the response curve

moved with it. This following motion indicated physically that the stage being tuned was resonating at the center frequency, and furthermore that the other stages were centered on the desired frequency because the stage being tuned completely controlled, within limits, the center frequency of the entire amplifier.

The center frequency of the amplifier was adjusted to 28.8 mcps, because this center frequency gave the most symmetrical overall response. It was noted that this center frequency of the response curve varied slightly with gain setting, and tended to increase from 28.6 mcps for a gain of 1500 to 28.8 mcps for a gain of 10,000. This observed frequency change is opposite to that which would be expected because the input capacitance of the two stages of variable gain would be expected to increase with gain, thus lowering the resonant frequencies of the circuits comprising the above capacitances.

The amplitude response of the amplifier was measured using the signal generator GR805-A51 and the Hewlett Packard Voltmeter 410-A. This is plotted in Figure 7, together with a computed phase characteristic for the first four stages which supply the modulating crystal.

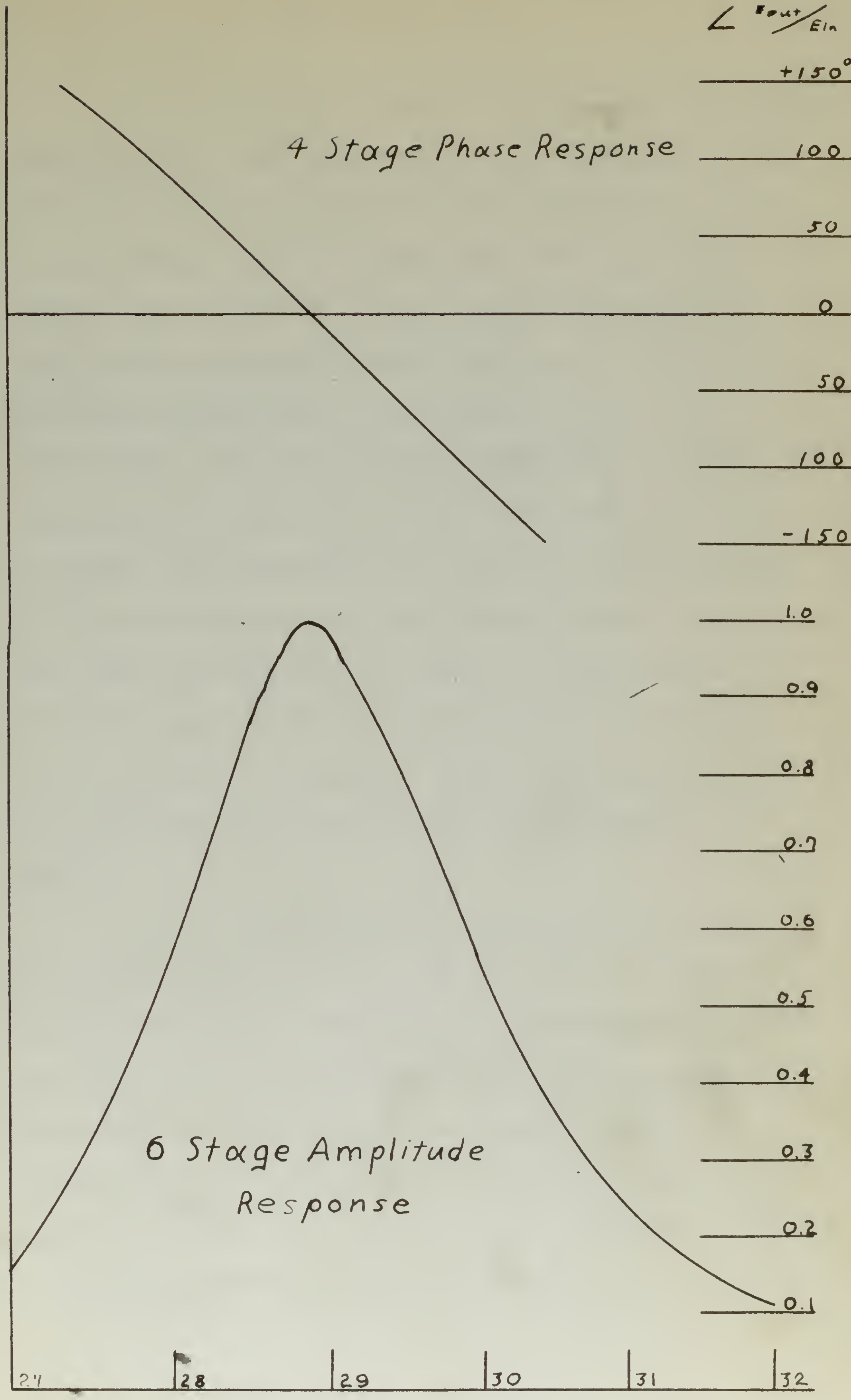


Figure 7

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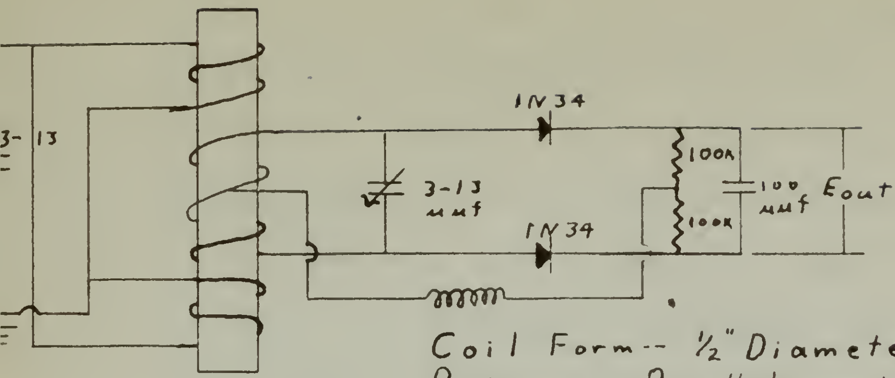
A cathode driven discriminator was constructed, see Figure 8. The response of the discriminator to a 1 volt input is plotted versus frequency in Figure 9. Because of lack of time, the coupling between the primary and secondary of the discriminator was not adjusted to optimize the amplifier and discriminator bandwidth relationship for steepest slope, i.e. greatest K_d. However, the discriminator response, Figure 9, is that of the second discriminator constructed. The bandwidth of the first discriminator was too narrow because the coupling between the primary and secondary was too small. With greater coupling, the discriminator bandwidth for linear response was 2 megacycles. This compares well with the amplifier which is 2 megacycles between 6 db points.

Before considering the design of the X-band wave guide assembly, it would be well to point out the most difficult aspect, the suppression of the sideband which is not transmitted by the cavity. This unwanted sideband is a spurious signal; the writer could not reduce it more than 8db below the level of the desired sideband at the detector crystal in the wave guide assemblies tested.



Coil Form -- ½" Diameter
Primary - Parallel windings - 12 turns - #30 wire
Secondary - C.T. - 24 turns -- #30 wire

Figure 8 Discriminator

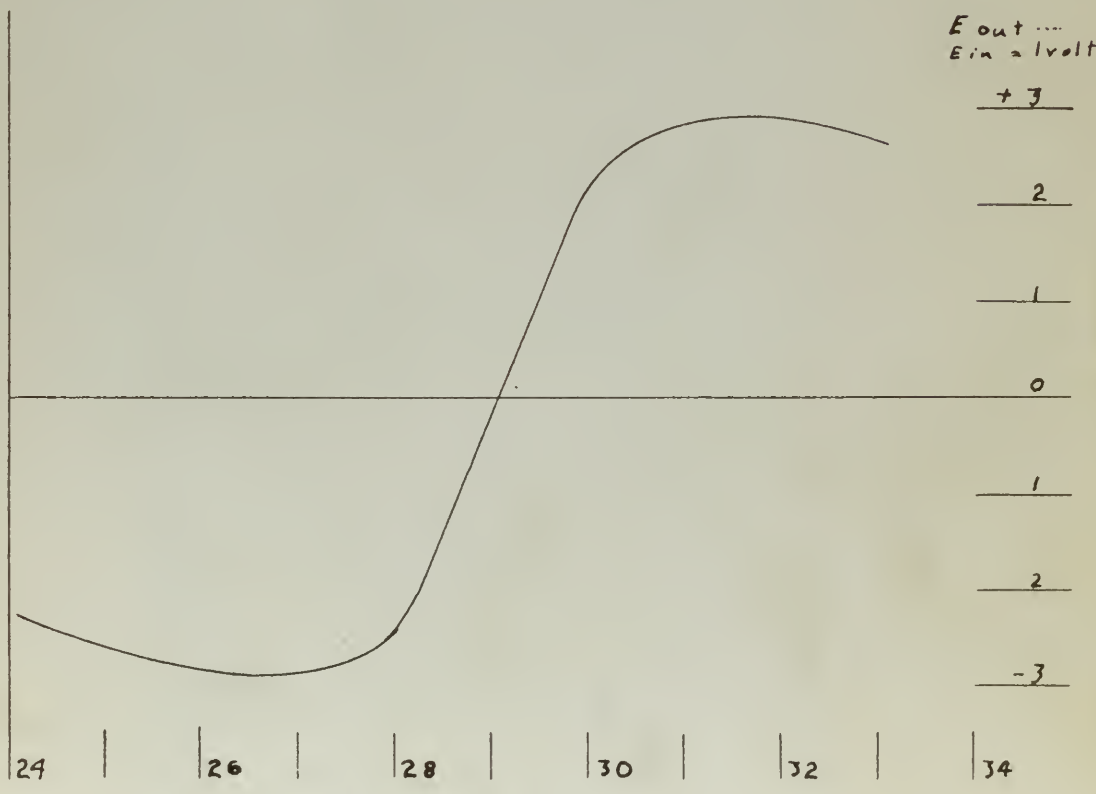


Figure 9 Discriminator Output

A second point to stress is that an important aim of this work was to achieve a broad-band system. (The system is inherently broad-band if the two electrical lengths shown in Figure 1 are equal.) Therefore, the use of matching sections was avoided.

The wave guide components used are listed below in Table I with their identifying numbers. The measured S.W.R. of each when terminated in a matched load is included.

TABLE I

Name of Component	Designating Letter (See Assembly Drawings)	Identifying Number	S. W. R.
Wave Guide 0.900" X 0.400"	---	---	----
90° E plane Bend	A	RLE Drawing #C10015	1.04
90° H plane Bend	B	RLE Drawing #C10016	1.07
Attenuator	C	TPX 27GM/25	1.04
Phase Shifter	D	Modification of C	1.04
Magic T	T	RLE Drawing #C11540	----
Cavity	M	1509TFX 26GA	2.43 at center frequency
Crystal Holder	H	RLE Drawing #B-85-A	1.32 with optimum bias current in 1N23A Crystal

To understand the drawings of wave guide assemblies, it must be remembered that the designating letters of Table I are used to identify wave guide components.

Figure 9-A represents the original wave guide assembly tested. The electrical length to Crystal B shown by the full line was carefully measured in the following manner. Crystal A with holder and the cavity were replaced by matched loads. Crystal B and holder were replaced by a SWR probe assembly terminated in a short. At a known oscillator frequency, f_1, the location of a particular minimum was measured and recorded. Then the probe was shifted to the next minimum nearer the source; as the oscillator frequency was decreased, this minimum was tracked until it reached the original recorded position. The new frequency, f_2, was measured. The following equations hold:

$$\text{Electrical length} = n\,\lambda g_1, \text{ at } f_1$$

$$\text{Electrical length} = (n - 1)\,\lambda g_2 \text{ at } f_2$$

Solution may be made for n since λg_1, and λg_2 may be computed. The electrical length is then known and equaled 39.43 cm. versus 40.9 cm. measured physically per Zaffarano's [5] method.

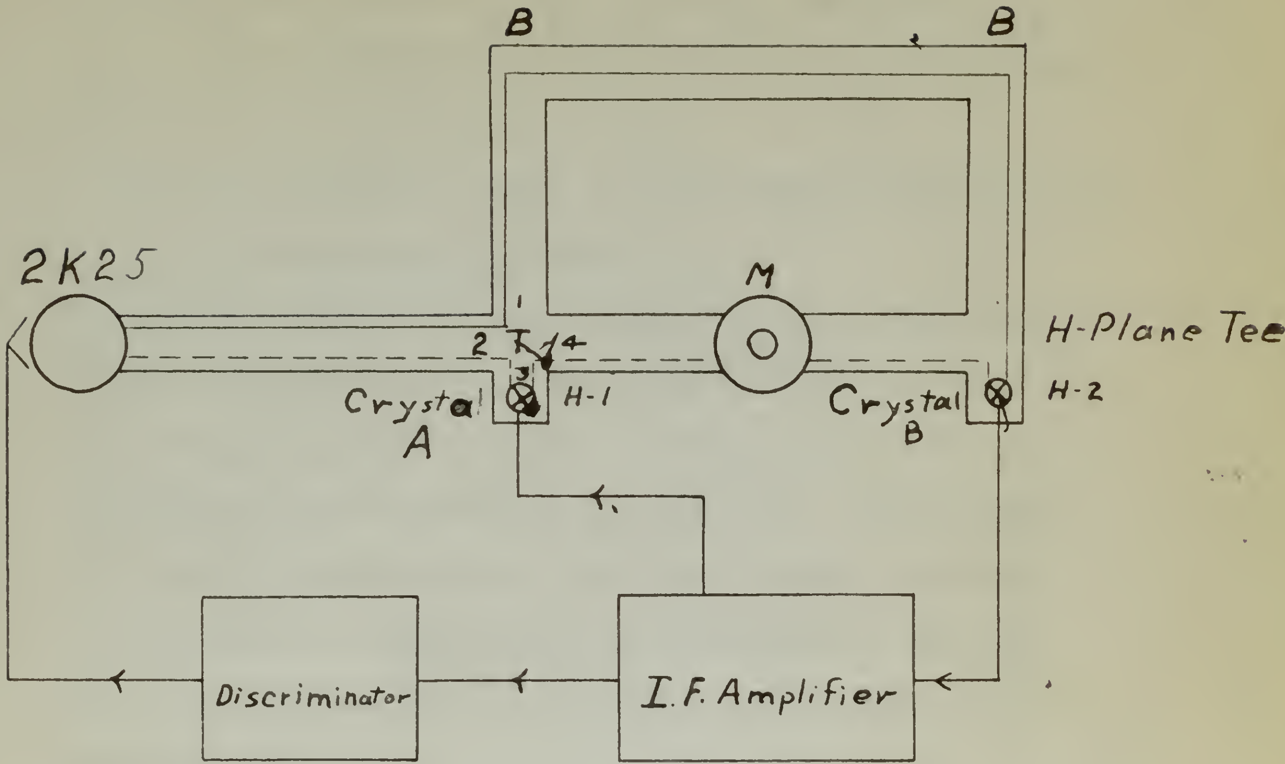


Figure 9-A Original System

A similar technique applied to the dashed path of Figure 9-A would be very difficult because:

a) A stabilized source would be needed because of the high Q cavity.

b) Crystal A would have to reflect considerable unmodulated energy.

For these reasons, it was decided to avoid this measurement at this particular point because it would be too costly in time. Rather, a phase shifter, D, was inserted between the Magic Tee and H-1. This addition would permit closing the loop between Crystals A and B with the amplifier immediately; and if this step was successful, the by-passed measurement could then be made.

It should be emphasized that to broadband the system the two paths of Figure 9-A must be equal. But this equality must be interpreted having in mind the fact that a major portion of the dashed path of Figure 9-A will be at a frequency 30 mcps greater than the oscillator frequency, since the upper sideband is to be used.

Using six place log tables, the following was computed.

TABLE II

f	g	Phase Difference For A Length of 25 cm	
8500 mcps	5.5523 cm	1621°	Difference
8530 mcps	5.5043 cm	1635°	14°
9000 mcps	4.8701 cm	1848°	
9030 mcps	4.8359 cm	1861.°1	13.°1
9500 mcps	4.3669 cm	2061°	
9530 mcps	4.3407 cm	2073.°4	12.°4

The above tabulation covering the designed band of the 2K25 klystron points out that a material difference exists but that this difference is practically constant. Therefore, if the difference is accounted for in equating tht two paths at any frequency, the equality will hold over the klystron tuning range.

When the loop was completed, a normal discriminator output curve was observed for very low amplifier gain settings. The observations were made by tuning the cavity and reading a voltmeter across the discriminator output terminals with the klystron frequency fixed. As the amplifier gain was raised

above 1500, an erratic voltage output from the discriminator existed indiscriminate of the cavity tuning.

The suspected cause of this performance was that a sideband, probably the lower though possibly both, was being reflected by the cavity and was traversing the path shown by the full line in Figure 9-A from the Magic Tee to Crystal B.

The transmission cavity in use, Model 1509TFX-26Ga, was a matched cavity in one direction. (As used in the waveguide assembly, Figure 9-A, the large entrance iris was connected to arm 4 of the Magic Tee. Although this cavity had a tuning range of only 200 mcps from 9000 to 9200 mcps, it was the only matched model available to the writer and consequently restricted the frequency range in all tests. It was felt that cavity cost precluded any experimental work in broadbanding Model 1527TFX-18GA which covers the complete 2K25 frequency range.) Using a Pound stabilized oscillator and Spectrum Analyzer, the S.W.R. of the cavity Model 1509TFX-26GA was measured at 9000 mcps and equalled 2.43. Similarly, the S.W.R. of the broad-band, unmatched cavity, Model 1527TFX-18GA, was 4.5. Even the matched cavity reflects some 20% of the incident power at resonance which would be the

desired upper sideband in operation, a loss of 1 db in transmission. However, the reflected signal is only 6 db down from the transmitted signal and will cause a spurious signal to appear if able to reach the detector crystal without being attenuated.

The first wave guide assembly successfully used is illustrated in Figure 10. The two Magic Tees were used to suppress the unwanted sideband. However, consider arm 4 of the input Magic Tee, Figure 11, terminated in the cavity (not at r.f. frequency) and arm 2 in a matched load. If r.f. energy is fed in arm 3 to a matched load in arm 1, the attenuation is only 8db as measured by a spectrum analyzer. Again, if both arms 4 and 2 are matched, the attenuation in the previous case increases to only 20db. Both observations were made at 9000 mcps.

The two attenuators were included in the wave guide assembly to assist in suppressing the unwanted signal. But these represent a compromise, at best, because C-2 attenuates the desired sideband and C-1 attenuates the carrier. Best results were obtained when C-2 was set on zero. For this case, consider the attenuation of the desired sideband versus the undesired sideband between crystals H-1 and H-2.

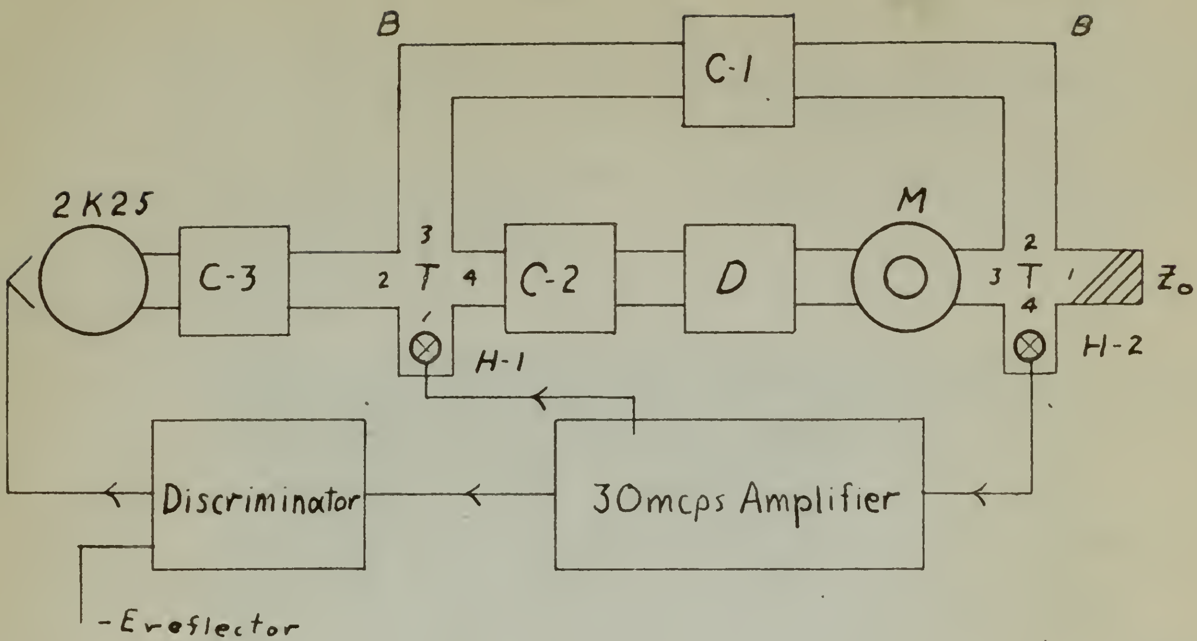


Figure 10 First System

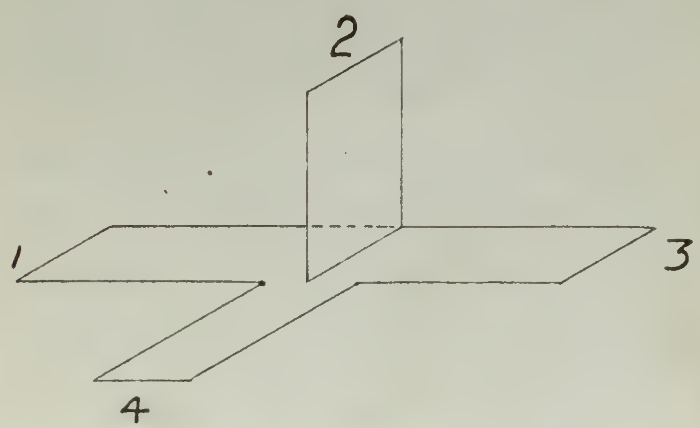


Figure 11 Magic Tee Schematic

Desired Sideband		Undesired Sideband	
Split in Magic T-1	3db	Measured attenuation in Magic T	8db
Cavity Attenuation Due to reflection as well as cavity loss in transmission.	7db	Attenuation in C-1	A
Split in Magic T-2	3	Split in Magic T-2	3
	13db		11 + Adb

It is apparent that 10db of attenuation must be inserted in C-1 to bring the undesired sideband 8db below the desired. This is the optimum figure arrived at by experimental observation.

The reflector of the 2K25 klystron was swept by a 60 cycle voltage, and the output of the discriminator was observed on a cathode ray oscilloscope, see Figure 12. This output, though of varying amplitude with frequency, was observed over a cavity tuning range of 70 mcps, which was 35 mcps each side of the center of the mode, in which range sufficient oscillator power was available. If the gain setting of the 30 mcps amplifier was increased, spurious signals began to appear on the oscilloscope screen.

This above oscillator power limitation over the mode was checked by mechanically tuning the

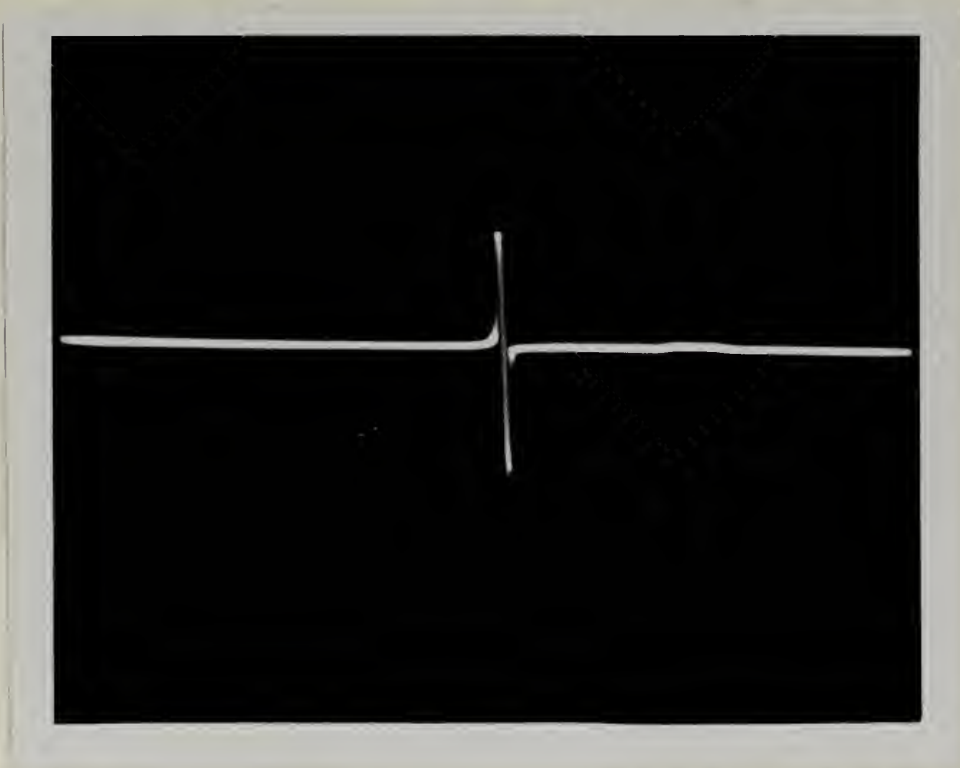


Figure 12

klystron about a fixed cavity frequency. The discriminator curve appeared, maximized, and disappeared on the screen over a 70 mcps range.

<u>The oscillator was stabilized with the equipment under discussion and forced to track over a range of 30 mcps with fixed klystron tuning.</u> The tracking in frequency was observed on a spectrum analyzer.

The second wave guide assembly to be used employed two Magic Tees and a directional coupler, Figure 13. Three different directional couplers with couplings of 10, 20, and 30 db were tested in the circuit. The greatest bandwidth was obtained using the 20db coupler; the discriminator output curve was visible on the oscilloscope screen over 100 mcps cavity tuning range, an improvement of 23%.

Lack of time prevented a complete study of this second system from being made. In neither the first nor second system was an attempt made to equalize the electrical lengths of the two paths. The basic reason for avoiding this problem was to devote more time to design, construction and study of wave guide assemblies which would suppress the undesired sideband.

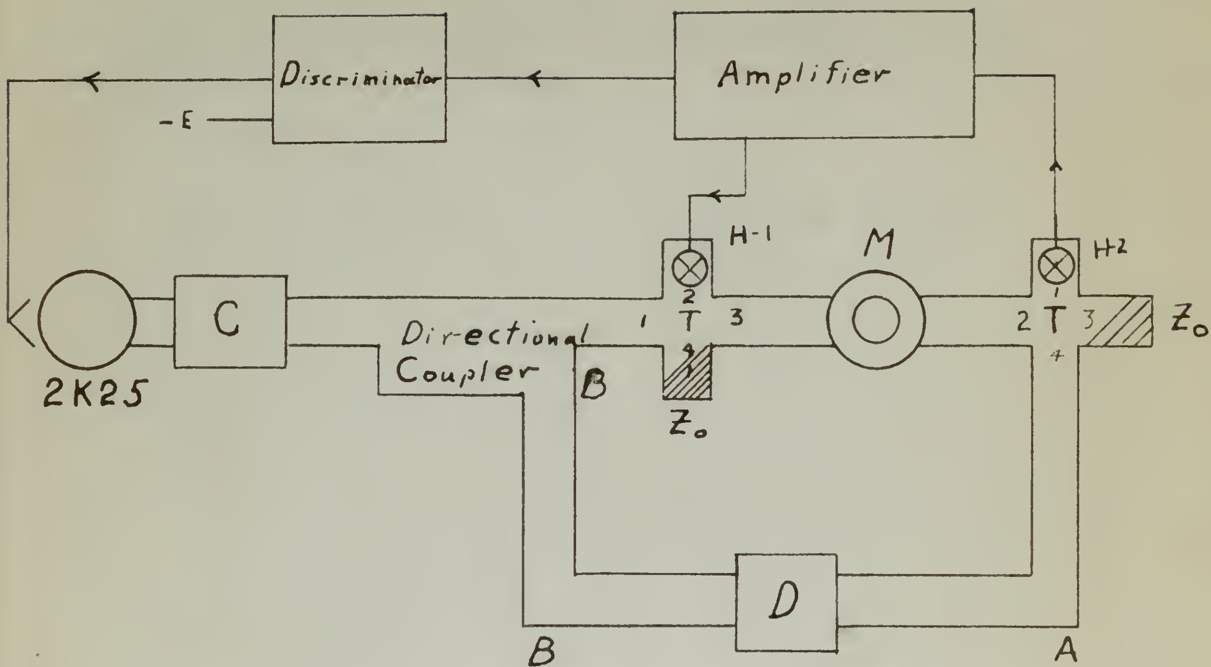


Figure 13 Second System

A broad-band system, then, was not constructed. However, once a wave guide assembly is built which will control the klystron with fixed mechanical tuning over a range of 150 mcps, the broad-banding problem may be easily handled as previously discussed.

CHAPTER III

CONCLUSIONS

A suitable wave guide configuration that would be able to take full advantage of this stabilization system was not achieved. Probably, the basic reason for this failure is that the wave guide assemblies used were too elaborate, since each element presented some mismatch which would make suppression of the undesired sideband more difficult. The wise direction for future efforts with this stabilization system would be to simplify the wave guide assembly.

It is believed that this system is by nature as frequency stable as the Pound system with modifications by Zaffarano. Though a moot point, the slope of the discriminator curve which is a measure of the stability of the system is a function of loop gain. Certainly, there is no physical reason apparent to the writer that would restrict this system's discriminator slope to less than that of the Pound system.

Before concluding this oblique comparison of the two systems, it would be well to point out that the reflection cavity used in the Pound system will normally have a higher loaded Q than the transmission

cavity used in the system under discussion. This point favors the Pound system in a measure.

Suggestions for Future Work

If the wave guide configuration of Figure 14 is employed, this Q differential no longer holds. This assembly was tested by the writer and was found to operate satisfactorily. No attempt was made to equalize the two electrical lengths shown by dotted and full lines; if they were equalized, the performance of the system should match that of the Pound system in stability and band-width. The chief difference between the Pound and this stabilizing scheme is that a Foster-Seeley discriminator is substituted for the I.F. Oscillator and "lock-in-mixer". Whether this substitution would be to advantage would be the subject of investigation.

A second suggestion for further work develops from the characteristic of the system which converts a cavity phase shift at 9000 mcps to a frequency differential at 30 mcps. If the phase-shift characteristic with frequency of the 30 mcps amplifier were accurately known (measuring apparatus is available at M.I.T.) then by measuring the frequency of the amplifier (at fixed oscillator and cavity frequencies

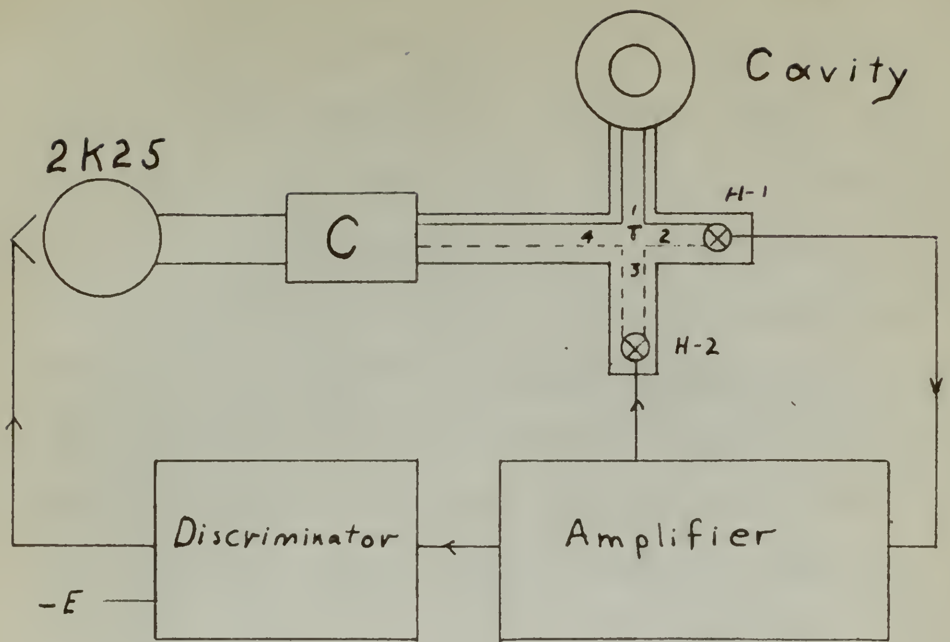


Figure 14 Proposed System

which are not necessarily the same) the phase shift caused by the cavity would be known because it equals in magnitude the amplifier phase shift. This conversion of phase change to frequency change, then, offers an interesting study in the field of measurements.

A third suggestion for further work is that, when a better wave guide assembly is perfected, the method be embraced in a frequency modulation system. In line with this suggestion, a second method of suppressing the cavity reflections upon arrival at the detector crystal will be briefly examined. That is to have the reflections arrive 180° out of phase for completing the amplifier-loop zero-phase requirements.

To broad-band this method of suppression, one solution is to have the carrier signal and the undesired sideband travel the same path. If this path length between the two crystals was sufficiently long, the differences shown in Table II would become sufficiently large. And so would the path length --- 127 inches long for 180° phase difference.

A reasonably broad-band could be arrived at by adjusting the lengths between the input Magic Tee junction of Figure 10 and the crystal in arm 1 and the cavity in arm 4 so that a 180° phase shift is

introduced between the carrier going directly into arm 3 and the sidebands going into arm 3 after reflection from the cavity. The overall path difference for the two signals could be $\lambda_g/2$; this small difference would not be too frequency sensitive over a 300 mcps band.

A second broad-band solution employing this method is also possible. The 180° phase shift may be introduced by an E plane Tee junction, as formed by arms 1, 2, and 3 of the Magic Tee, Figure 11. And since the lower sideband will require a longer path length than the carrier which traverses its normal path, Figure 10, this difference may be made up in the crystal and cavity spacings from the Tee junction.

A fourth suggestion for future work is to develop mathematically the relationship that should exist between the bandwidths of an amplifier and its discriminator to achieve the greatest slope in the discriminator output.

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